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(54) **MEASURING ABSOLUTE STATIC PRESSURE AT ONE OR MORE POSITIONS ALONG A MICROFLUIDIC DEVICE**

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(52) **U.S. Cl.** **73/202**; 73/747
(58) **Field of Search** 73/706, 715–727, 73/756, 514.16, 514.17, 861.65, 862.581, 862.582, 862.59, 861.42, 861.45, 861.47, 195, 196, 747, 202, 203; 361/283.1–283.4

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5,316,619	A	5/1994	Mastrangelo
5,332,469	A	7/1994	Mastrangelo
5,369,544	A	11/1994	Mastrangelo
5,458,000	A	10/1995	Burns et al.
5,528,939	A	6/1996	Martin et al.
5,679,902	A	10/1997	Ryhanen
5,808,210	A	9/1998	Herb et al.
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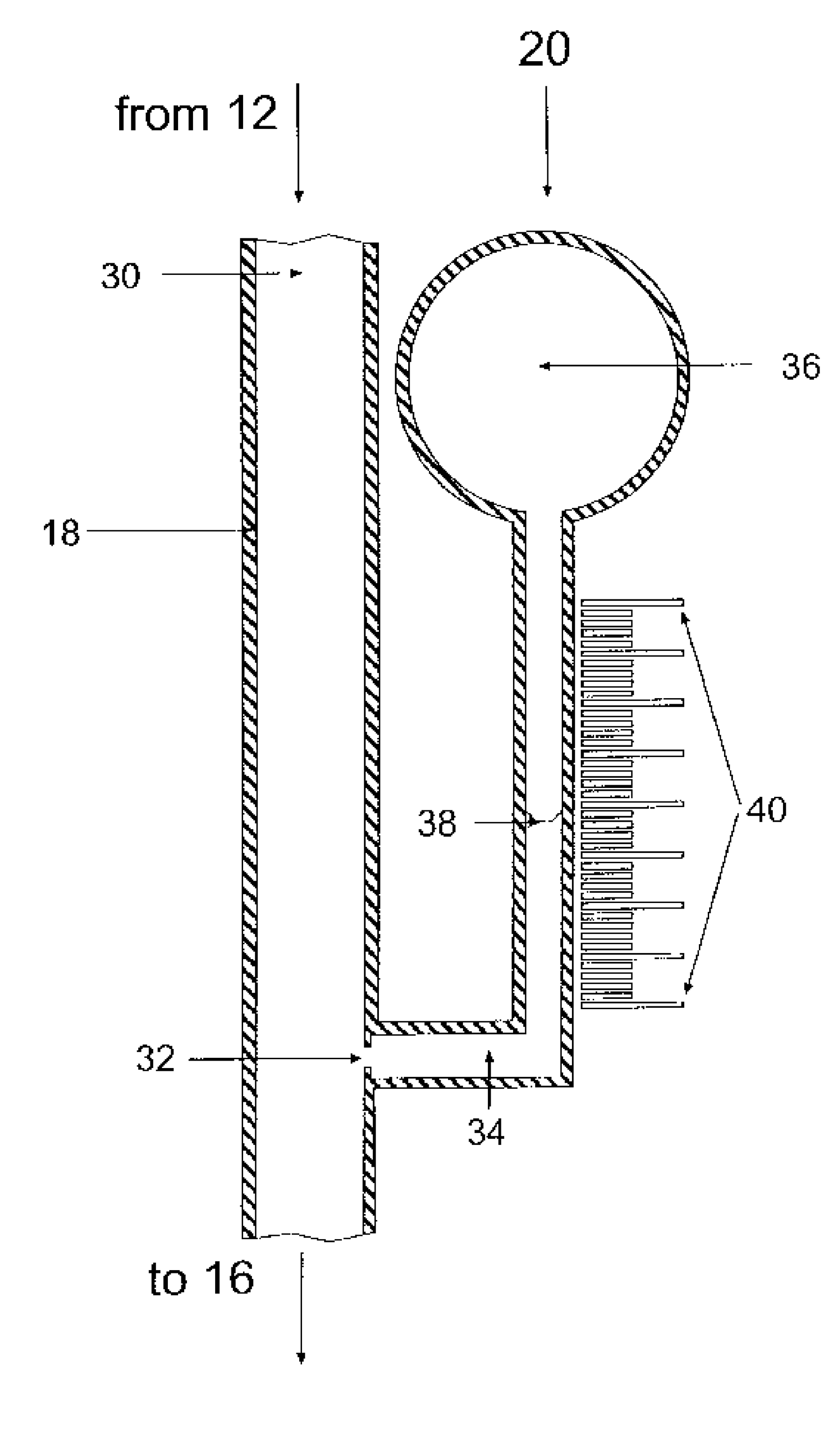
(57) **ABSTRACT**

A method of measuring absolute static pressure at one or more positions along the wall of a microfluidic device transporting a working fluid that is immiscible in a first selected gas environment, includes providing a first fluid conducting channel having an atmosphere provided by the selected gas environment under a sealed environment and in communication with the microfluidic device at a first point of communication; providing a visual scale adjacent to the first fluid conducting channel; and transporting the working fluid under pressure conducted by the microfluidic device into the first fluid conducting channel such that the volume transported into such first fluid conducting channel varies depending upon the absolute static pressure of the working fluid at the first point of communication, whereby the absolute static pressure at the first point of communication is visually determined depending on the position of the interface of the working fluid and the first selected gas environment in the first fluid conducting channel when compared with the first visual scale.

10 Claims, 4 Drawing Sheets



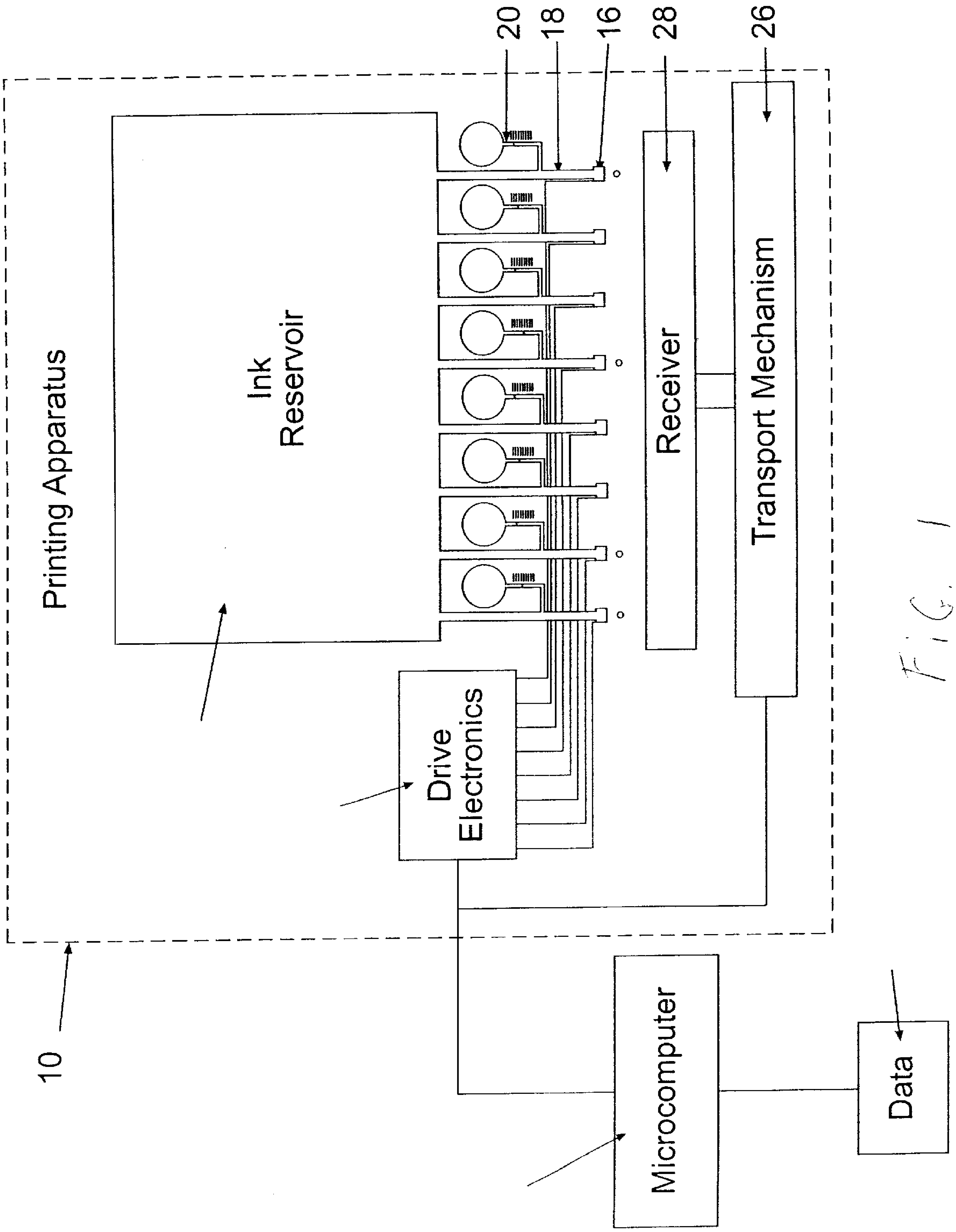

20
18
16
28
26
Printing Apparatus
Ink
Reservoir
Receiver
Transport Mechanism
Drive
Electronics
10
Microcomputer
Data

FIG. 1

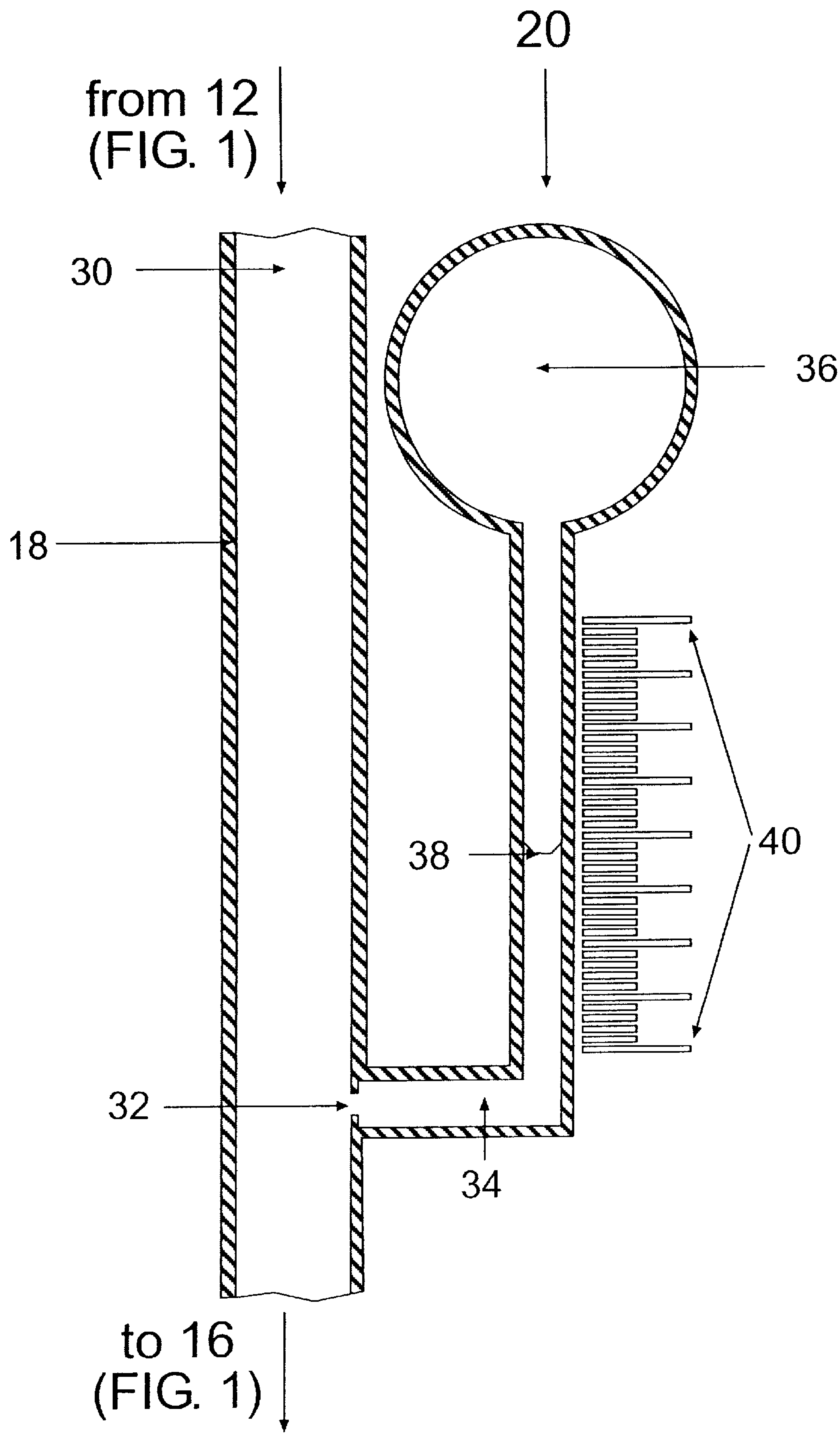


FIG. 2

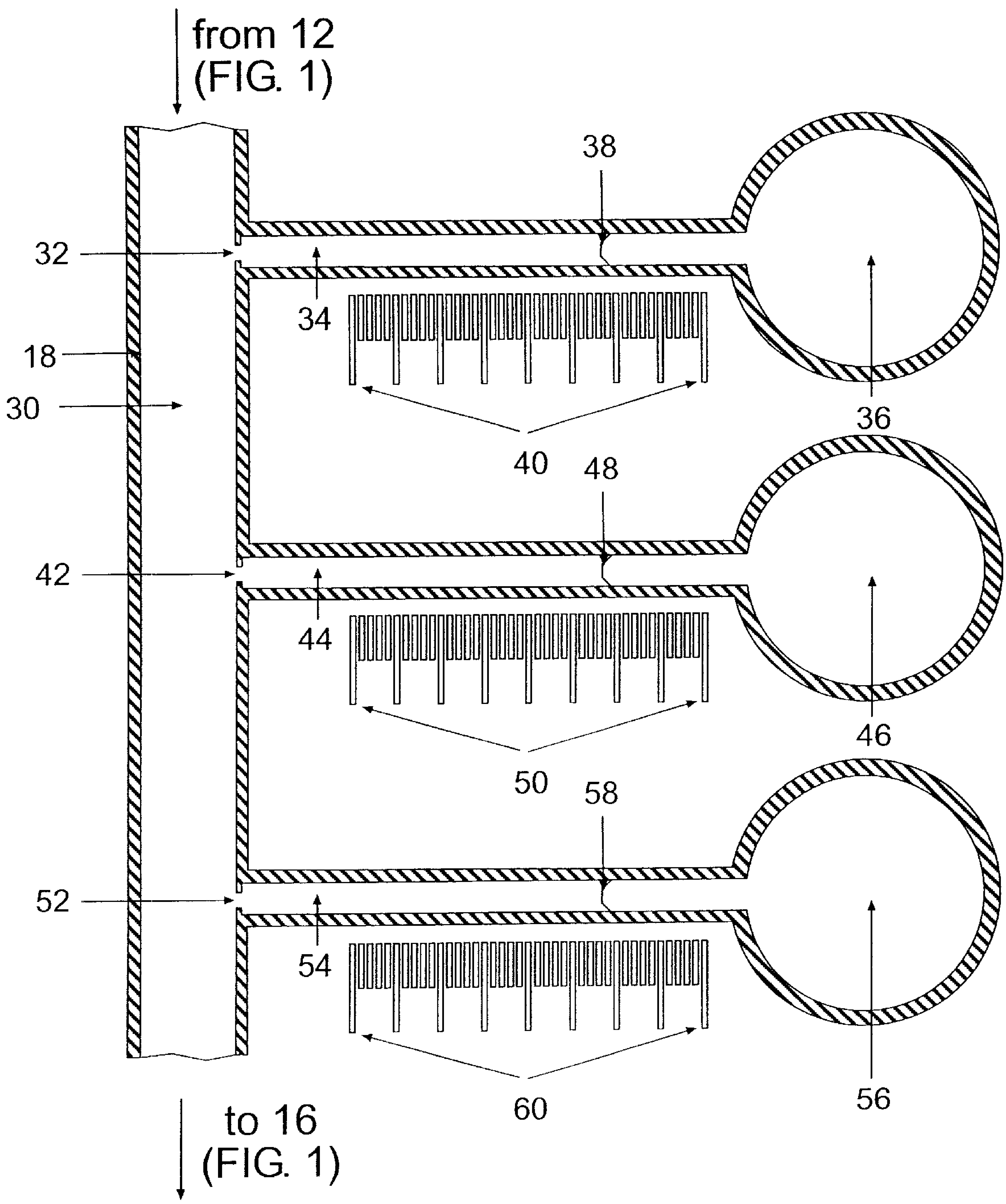

from 12
(FIG. 1)
38
32
34
18
30
36
40
48
42
44
46
50
58
52
54
56
60
to 16
(FIG. 1)

FIG. 3

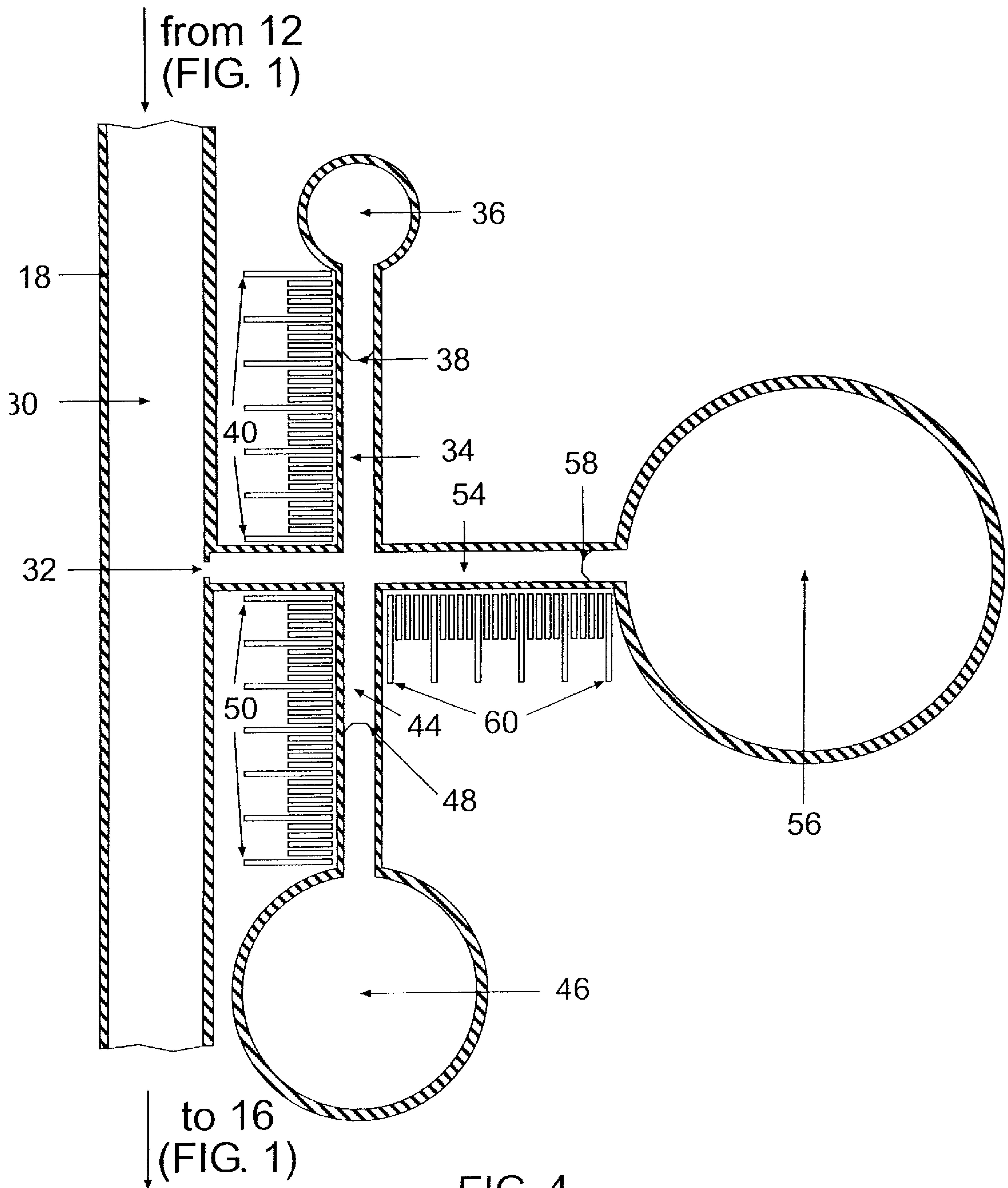


FIG. 4

MEASURING ABSOLUTE STATIC PRESSURE AT ONE OR MORE POSITIONS ALONG A MICROFLUIDIC DEVICE

FIELD OF THE INVENTION

The present invention relates to measuring the absolute static pressure of fluid flowing in a microfluidic device.

BACKGROUND OF THE INVENTION

Conducting of fluid in microfluidic devices is frequently done in inkjet printers. It is also done in other types of microfluidic devices in fields not related to printing, for example, drug delivery and microscale biological and chemical analysis. In the inkjet printing field, ink is transported from a reservoir to a printhead, where it is sprayed onto print media. If a nozzle becomes clogged, the absolute static pressure within the relevant ejection chamber may exceed normal values. Thus, absolute static pressure detection can be used as a nozzle-by-nozzle diagnostic tool in the case of an inkjet printer. Similarly, absolute static pressure sensing in drug delivery systems is critical due to the potential hazards of inaccurate dosing. In microscale biological and chemical analysis systems, where precision is critical, an integrated absolute static pressure sensor reduces the error associated with sensing the absolute static pressure across an intervening volume between the microfluidic device and a non-integrated sensor; in addition, an integrated pressure sensor reduces the volume of fluid that must be sacrificed to measure the pressure. This increases cost and waste, and in the case of biological analysis systems, for example, it increases the required sample size, making sample collection and preparation more difficult and costly.

While prior art exists for pressure drop measurement across microfluidic and macrofluidic systems, even microscale measurement systems are integrated on the macroscale, allowing measurement of absolute static pressure as the working fluid enters or exits a microfluidic device, but not while the working fluid is within the interior of the microfluidic device. For example, U.S. Pat. No. 4,426,768 teaches the use of the measurement of a strain-dependent property to deduce the local absolute pressure of a non-conductive fluid. Similarly, U.S. Pat. No. 4,463,336 teaches the measurement of absolute gas pressure using the varying resistance of a narrow piezoresistive bridge. Electrically conductive liquids cannot be measured with this sensor. U.S. Pat. No. 4,682,503 teaches the use of measuring the varying thermal resistance of a silicon nitride bridge to the same end. This sensor does not work with an electrically conducting fluid, and struggles to provide accurate data with a fluid of high heat capacity. A number of sensors measuring pressure via the capacitance between a deforming membrane and a fixed electrode have been previously disclosed. U.S. Pat. Nos. 5,305,643; 5,316,619; 5,369,544 and 6,109,113 teach the measurement of absolute pressure against a standard (normally vacuum or the ambient atmosphere) by capacitance, while U.S. Pat. Nos. 5,332,469; 5,679,902 and 6,012,335 teach the use of capacitance to measure the relative difference of two varying pressures. In all cases, the region across which the field is applied must not be penetrated by any fluid with a different dielectric constant from that of the fluid originally between the two plates. U.S. Pat. No. 5,458,000 teaches the use of a second resonant sensor that is not affected by changes in pressure but responds to changes in temperature for use in temperature error compensation. This sensor will not operate in a viscous fluid. U.S. Pat. Nos. 5,528,939 and 5,939,635 teach the measurement of energy needed to move a resonant member near a stationary surface, where the damping losses are highly pressure dependent. This can only be used to measure a compressible working fluid, however, or the variation in damping force will not be evident. U.S. Pat. No. 5,808,210 teaches measurement of absolute pressure by measuring deformation either electrically or optically. While this sensor can be used for optical measurement of the membrane deflection, it cannot be used with an opaque working fluid.

SUMMARY OF THE INVENTION

It is an object of the present invention to provide an improved way to measure the absolute static pressure in a microfluidic device transporting a working fluid.

This object is achieved in a method of measuring absolute static pressure at one or more positions along the wall of a microfluidic device transporting a working fluid that is immiscible in a first selected gas environment, comprising the steps of:

(a) providing a first fluid conducting channel having an atmosphere provided by the first selected gas environment under a sealed environment and in communication with the microfluidic device at a first point of communication;

(b) providing a first visual scale adjacent to the first fluid conducting channel; and

(c) transporting the working fluid under pressure conducted by the microfluidic device into the first fluid conducting channel such that the volume transported into such first fluid conducting channel varies depending upon the absolute static pressure of the working fluid at the first point of communication, whereby the absolute static pressure at the first point of communication is visually determined depending on the position of the interface of the working fluid and the first selected gas environment in the first fluid conducting channel when compared with the first visual scale.

It is an advantage of the present invention to visually inspect the volume in a first fluid conducting channel in communication with the microfluidic device to readily determine the absolute static pressure in the first fluid conducting channel without the need for electrical elements or moving parts.

It is an advantage of the present invention to integrate the absolute static pressure sensor with nearly any existing microfluidic device without modification of the fabrication process of the microfluidic device.

It is an advantage of the present invention that the integration referred to above will not increase the fabrication cost of the pre-existing microfluidic device.

It is a further advantage of the present invention to measure absolute static pressure over a variety of pressure ranges at the same point of communication, thereby increasing the effective absolute static pressure range of the sensor.

It is a further advantage of the present invention to measure absolute static pressure at a precise location within a microfluidic device.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** depicts a schematic of an ink jet printing apparatus that has a microfluidic device in which the present invention is adapted to measure the absolute static pressure therein;

FIG. **2** is a schematic of a first embodiment of the present invention;

FIG. **3** is a schematic of a second embodiment of the present invention; and

FIG. **4** is a schematic of another embodiment of the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

The term, "microfluidic", "microscale" or "microfabricated" generally refers to structural elements or features of a device, such as fluid channels, chambers or conduits, having at least one fabricated dimension in the range from about 0.1 μm to about 500 μm. In devices according to the present invention, the microscale channels or chambers preferably have at least one internal cross-section dimension, e.g., depth, width, length, diameter, etc., between about 0.1 μm to about 500 μm, preferably between about 1 μm to about 200 μm.

The microfluidic devices described in the present invention are preferably fabricated with the techniques commonly associated with the semiconductor electronics industry, e.g., photolithography, dry plasma etching, wet chemical etching, etc., on the surface of a suitable substrate material, such as silicon, glass, quartz, ceramics, as well as polymeric substrates, e.g., plastics.

Various techniques using chip technology for the fabrication of microfluidic devices, and particularly microcapillary devices, with silicon and glass substrates have been discussed by Manz, et al. (*Trends in Anal. Chem.* 1990, 10, 144, and *Adv. In Chromatog.* 1993, 33, 1). Other techniques such as laser ablation, air abrasion, injection molding, embossing, etc., are also known to be used to fabricate microfluidic devices, assuming compatibility with the selected substrate materials.

The present invention uses a method of measuring absolute static pressure at one or more positions along the wall of a microfluidic device transporting a working fluid that is immiscible in a first selected gas environment, comprising the steps of: providing a first fluid conducting channel having an atmosphere provided by the first selected gas under a sealed environment and in communication with the microfluidic device at a first point of communication; providing a visual scale adjacent to the first fluid conducting channel; and transporting the working fluid under pressure conducted by the microfluidic device into the fluid conducting channel such that the volume transported into such first fluid conducting channel varies depending upon the absolute static pressure of the working fluid at the first point of communication, whereby the absolute static pressure at the first point of communication can be visually determined depending on the position of the interface of the working fluid and the first selected gas environment in the first fluid conducting channel when compared with the first visual scale. If the volume occupied by the first selected gas environment is known at static conditions and the absolute static pressure is known under ambient conditions, then the absolute static pressure during operation can be determined by the motion of the interface between the working fluid and the first selected gas environment, using, for example, the ideal gas law,

$$PV=nRT,$$

where P represents the absolute static pressure of the first selected gas environment, which is presumed to be related in a known way to the absolute static pressure of the working fluid at the first point of communication, V represents the volume occupied by the first selected gas environment, n represents the number of moles of gas in the first selected gas environment, R represents a universal gas constant, and T represents the absolute temperature of the first selected gas environment. For steady-state working fluid/selected gas environments, the following relation applies:

$$P_{fluid} = P_{gas} - \sigma\left(\frac{1}{R_1} + \frac{1}{R_2}\right)\cos\theta$$

where P_{fluid} is the absolute static pressure of the working fluid at the point of communication; P_{gas} is the absolute static pressure of the first selected gas environment; R_1 and R_2 are the local radii of curvature of the interface between the first selected gas environment and the working fluid; θ is the contact angle of the three-phase system formed by the working fluid, the first selected gas environment, and the wall of the microfluidic device; and σ is the surface tension of the three-phase system described above. In cases where the surface tension is very small, ($\sigma \rightarrow 0$), the absolute static pressure of the working fluid may be considered equal to the absolute static pressure of the selected gas environment. Hence, the present invention can measure absolute static pressure at a precise location within a microfluidic device.

More complex models that relate absolute static pressure, volume, and temperature to physical constants can also be used to improve accuracy. For example, the additional terms in the van der Waals or "real gas" equation (shown below) will improve accuracy for cases where a higher density of gas molecules causes stronger intermolecular interaction.

$$\left(P + \frac{C_1}{V^2}\right)(V - C_2) = nRT$$

In this equation the two additional constants C_1 and C_2 are determined by the type of gas in the first selected gas environment.

Turning now to FIG. **1**, a schematic diagram is shown of a printing apparatus **10** including at least one ink reservoir **12**, drive electronics **14**, and a plurality of individually addressable printheads **16** in communication with both the ink reservoirs **12** and the drive electronics **14**. Ink is introduced into each individually addressable printhead **16** by means of a microfluidic device **18**, in this case a microfluidic channel, which in turn is in communication with an absolute static pressure sensor **20**. A computer **22** receives or generates data **24** representing, for example, a digital image. The computer **22** also controls the output to the printing apparatus **10** by means of electrical signals to the drive electronics **14**. The drive electronics **14** in turn control a transport mechanism **26**, which conveys a receiver **28** to the individually addressable printheads **16** so that ink pixels may be transferred to the receiver **28**. The ink flow may be controlled by any means including but not limited to thermal ejection, piezoelectric ejection, or electrostatic ejection. The computer **22** also controls the individually addressable printheads **16**.

FIG. **2** depicts a first embodiment of the absolute static pressure sensor **20** shown in FIG. **1**, that measures absolute static pressure in a working fluid **30** at the first point of communication **32** of a first fluid conducting channel **34** with the microfluidic device **18**. The working fluid **30** may be, but is not limited to any of the following fluids: water, ink, ethylene glycol, methanol, ethanol, isopropanol, oil, acetone, an organic solvent, a biological fluid, a solution of a chemical analyte, or a miscible combination of these. The first point of communication **32** should be kept as small as possible to minimize disruption to the flow in the microfluidic device **18**; however, if the first point of communication **32** is too small, the response time of the absolute static pressure sensor **20** will become large, since equilibration of the absolute static pressure sensor **20** will be limited by the rate at which the working fluid **30** can flow through the first point of communication **32**.

In addition to the use of the present invention to measure the absolute static pressure in a microfluidic channel, the absolute static pressure sensor **20** can measure the absolute static pressure at any point in a microfluidic device **18**; including, but not limited to a channel, reservoir, chamber, pump, valve, mixer, needle, or any system incorporating any combination of these. For example, the absolute static pressure of an ink chamber can be measured by placing a first fluid conducting channel **34** in communication with the ink chamber.

Generally, the placement of the sensor **20** is that the point of communication **32** should be located where the local working fluid velocity during normal operation is parallel to the plane of the point of communication **32**. If the working fluid **30** can exert momentum in the direction normal to the plane of the point of communication **32**, the absolute static pressure registered by the absolute static pressure sensor **20** will not be the absolute static pressure of the working fluid **30** at the first point of communication **32**, but rather the absolute stagnation pressure of the working fluid **30** at the first point of communication **32**, if the local fluid velocity vector is normal to the plane of the first point of communication **32**, or some intermediate value between these two pressures if the local working fluid velocity vector impacts the plane of the first point of communication **32** at some angle between zero and ninety degrees.

When the individually addressable printhead **16** is primed with a working fluid **30** (in this case ink) before use by the drive electronics **14**, the microfluidic device **18** will fill with fluid. Depending on the pressure used to prime the absolute static pressure sensor **20** and the ambient pressure conditions upon filling, a certain amount of gas will be trapped within a first fluid conducting channel **34**, forming a first selected gas environment **36** at the end of the first fluid conducting channel **34**. This first selected gas environment **36** may be air, nitrogen, argon, neon, helium, oxygen, hydrogen, water vapor, carbon monoxide, carbon dioxide or a miscible combination of these. The limitations on the selected gas environment **36** are that the gas must be immiscible with the working fluid **30** and non-reactive in the presence of the working fluid **30**. Similarly, for non-inkjet microfluidic devices, there will be an initial filling of the microfluidic device **18** generally accomplished by forcing the working fluid **30** through the microfluidic device **18** using an external pressure source. In order to use the absolute static pressure sensor **20**, the initial volume of this first selected gas environment **36** must be determined by optically comparing the position of a first interface **38** to a first visual scale **40** while the absolute static sensor **20** is under ambient pressure. The use of the visual scale **40** obviates the need for electrical elements or moving parts. This in turn means that the absolute static pressure sensor **20** integrates with nearly any existing microfluidic device without modification of the fabrication process of the microfluidic device. Therefore, this integration will not increase the fabrication cost of the pre-existing microfluidic device.

Subsequently, the first interface **38** position relative to the first visual scale **40** can be measured to determine the volume of the first selected gas environment **36**. It is important to note that there are no restrictions on the optical properties of the working fluid **30**. It can be opaque or transparent, as refraction of light near the first interface **38** will cause the interface to appear dark even if the working fluid **30** is transparent. Obviously, the first interface **38** between an opaque working fluid **30** and a transparent first selected gas environment **36** is easily optically resolvable. Using the initial volume, measured under ambient static conditions, and an equilibrium volume, measured while the microfluidic device is in operation, the operating absolute static pressure can be determined. Since a fixed amount of gas is trapped within the first selected gas environment **36**, the following relation for the operational absolute static pressure, P_2, holds under isothermal equilibrium conditions as a direct result of the ideal gas law:

$$P_2 = P_1 \frac{V_1}{V_2}$$

where P_1 is the ambient absolute static pressure (measured with, for example, an external barometer) at which V_1, the initial volume, is measured and P_2 is the operational absolute static pressure at which V_2, the operational volume, is measured. In addition to this rigorous determination of absolute static pressure under isothermal equilibrium conditions, the absolute static pressure sensor **20** can qualitatively determine the effectiveness of an individually addressable printhead **16** relative to its neighbors. If the first selected gas environment **36** of a certain absolute static pressure sensor **20** ceases to register changes in volume while the first selected gas environments of the absolute static pressure sensors **20** of all neighboring individually addressable printheads **16** continue to register fluctuations in volume, a defective or broken individually addressable printhead **16** can be detected during operation. Similarly, if the volume fluctuations of the first selected gas environment in one absolute static pressure sensor **20** indicate an inordinately large absolute static pressure change in one individually addressable printhead **16**, a partial or total blockage of the microfluidic device **18** may have occurred. If the interrogation process is automated by the integration of an optical detection device, such as a CCD array (not pictured), then the printing apparatus **10** will have the ability to dynamically diagnose failure of certain individually addressable printheads **16** and direct the drive electronics **14** to correct for this failure. These benefits extend beyond the domain of inkjet printing into other applications. For example, microfluidic device releasing a steady dose of a drug through a microfluidic needle, a sudden drop in absolute static pressure (rise in volume) would be indicative of a blockage upstream, or a failure of the ink reservoir **12** or other pressure source driving the flow. Conversely, a rise in absolute static pressure would indicate a blockage downstream, causing the entire microfluidic device **18** to equilibrate to a higher absolute static pressure, since the majority of the absolute static pressure loss would occur across the blockage.

FIG. **3** depicts a second embodiment of the absolute static pressure sensor **20** shown in FIG. **1**. Absolute static pressure is measured at multiple points along the microfluidic device **18**. As with the first point of communication **32**, a second point of communication **42** and any additional points of communication **52** should be kept as small as possible to minimize disruption to the flow in the microfluidic device **18**. However, if the second point of communication **42** or any additional point of communication **52** is too small, the response time of the absolute static pressure sensor **20** will become large, since equilibration of the absolute static pressure sensor **20** will be limited by the rate at which fluid can flow through the second point of communication **42** or the additional point of communication **52**, respectively. When the individually addressable printhead **16** is primed with a working fluid **30** (in this case ink) before use by the drive electronics **14**, the microfluidic device **18** will fill with fluid. Depending on the pressure used to prime the absolute static pressure sensor **20**, and the ambient pressure conditions upon filling, a certain amount of gas will be trapped within the first fluid conducting channel **34**, the second fluid conducting channel **44**, and any additional fluid conducting channels **54**, forming a first selected gas environment **36** at the end of the first fluid conducting channel **34**, a second selected gas environment **46** at the end of the second fluid conducting channel **44**, and additional selected gas environments **56** at the ends of the additional fluid conducting channels **54**.

For non-inkjet microfluidic devices, there will be an initial filling of the microfluidic device **18** generally accomplished by forcing the working fluid **30** through the microfluidic device **18** using an external pressure source. In order to use the absolute static pressure sensor **20** the initial volume of this first selected gas environment **36** must be determined by optically comparing the position of the first interface **38** to the first visual scale **40** while the absolute static pressure sensor **20** is under ambient pressure. Similarly, the initial volume of the second selected gas environment **46** must be determined by optically comparing the position of the second interface **48** to the second visual scale **50** while the absolute static pressure sensor **20** is under ambient pressure, and the initial volume of any additional selected gas environment **56** must be determined by optically comparing the position of the additional interface **58** to an additional visual scale **60** while the absolute static pressure sensor **20** is under ambient pressure.

Subsequently during microfluidic device operation, measurements of the first interface **38** position relative to the first visual scale **40** can be made to determine the volume of the first selected gas environment **36**, measurements of the second interface **48** position relative to the second visual scale **50** can be made to determine the volume of the second selected gas environment **46**, and measurements of any additional interface **58** position relative to the additional visual scale **60** can be made to determine the volume of the additional selected gas environment **56**. Using the initial volume measured under ambient static conditions and an equilibrium operational volume measured while the microfluidic device **18** is in operation, the operational absolute static pressure can be determined. Since a fixed amount of gas is trapped within each of the selected gas environments **36**, **46**, and **56**, the following relation holds for each operational absolute static pressure, P_2, under isothermal equilibrium conditions as a direct result of the ideal gas law:

$$P_2 = P_1 \frac{V_1}{V_2}$$

where P_1 is the ambient absolute static pressure (measured with, for example, an external barometer) at which V_1, the initial volume, is measured and P_2 is the operational absolute static pressure at which V_2, the operational volume, is measured. As described above, more complex non-ideal and/or gas-specific relationships between P_1, V_1, P_2 and V_2 can be used for this calculation to model, for example diatomic vs. monatomic gases.

After calculating the absolute static pressure at each point of communication **32**, **42** or **52**, the static pressure differential from one point of communication **32**, **42** or **52**, to another can be determined by subtracting the calculated absolute static pressures from one another. By dividing the static pressure differential between two points of communication **32**, **42** or **52**, by the distance between the two points of communication **32**, **42** or **52**, an average static pressure gradient between the two absolute static pressure sensors **20** can be determined. Using the physical properties of the working fluid in combination with predetermined formulae for laminar flow in microfluidic channels with various geometrical cross sections (see, for example, *Viscous Fluid Flow* by Frank White, second edition, pp. 119–121) the flow rate can then be determined. For example, for a microfluidic channel with rectangular cross-section (a common cross-section for micromachined microfluidic channels), the flow rate would be determined by the following equation:

$$Q = \frac{4ba^3}{3\mu}\left(\frac{-\Delta P}{\Delta L}\right)\left[1 - \frac{192a}{\pi^5 b}\sum_{i=1,3,5,\ldots}^{\infty}\frac{\tanh(i\pi b/2a)}{i^5}\right]$$

where Q is the flow rate of a working fluid of absolute viscosity μ through a rectangular microfluidic channel of width $2a$ and height $2b$, and ΔP is the measured static pressure differential between two points of communication **32**, **42**, and/or **52** separated by a distance ΔL. Furthermore, by performing this calculation between several combinations of points of communication, the accuracy of the flow rate calculation can be confirmed. This capability also lends itself to analysis of microfluidic device clogging, localization of the region of failure of the microfluidic device **18**. When the absolute static pressure downstream of a particular region drops while the upstream absolute static pressure remains constant, the source of the static pressure differential must be between the upstream and downstream absolute static pressure sensor.

FIG. **4** depicts a third embodiment of the absolute static pressure sensor **20** shown in FIG. **1**, that measures absolute static pressure over several pressure ranges at its single first point of communication **30** with the microfluidic device **18**. By varying the ratio of the volume of the selected gas environments **36**, **46** or **56** to the cross-sectional areas of their respective fluid conducting channels **34**, **44** or **54**, an absolute static pressure sensor **20** is created that can measure absolute static pressure over a variety of ranges, since the displacement of each interface **38**, **48** or **58** is determined by the following relationship:

$$\Delta x = \frac{-\Delta V}{A} = \frac{\Delta P}{P_1}\frac{V_2}{A}$$

where Δx is the change in interface **38**, **48** or **58** position, ΔV is the change in the volume of the corresponding selected gas environment **36**, **46** or **56**, and A is the cross-sectional area of the microfluidic channel. When the absolute static pressure sensor **20** experiences small changes of the absolute static pressure from ambient static pressure in the working fluid **30** at the first point of communication **32**, the volume of the selected gas environment **36**, **46** or **56** will show a correspondingly small change in volume.

In the embodiment depicted in FIG. **4**, the displacement from equilibrium of the first fluid interface **38** would be less than the displacement of the second fluid interface **48**, which in turn would be less than the displacement of the additional interface **58**. This can be magnified by using a larger additional selected gas environment **56**, so that the change in volume ΔV is more evident, and/or by making the additional fluid conducting channel **54** narrower, so that the cross-sectional area A of the additional fluid conducting channel **54** decreases, increasing the linear displacement Δx of the additional interface. Thus, a narrow fluid conducting channel **34**, **44** or **54** and a large selected gas environment **36**, **46** or **56** are advantaged in accurately measuring a small change in absolute static pressure, which might be undetectable in a wider fluid conducting channel **34**, **44** or **54** with a smaller selected gas environment **36**, **46** or **56**. However, the same sensor would not be able to measure large absolute static pressure changes, since the change in volume would compress the selected gas environment **36**, **46** or **56** to a point where the interface **38**, **48** or **58** position could no longer be measured on the visual scale **40**, **50** or **60**. By using additional sensors in communication with the microfluidic device **18** at the same point of communication **32**, the higher absolute static pressure can be measured on a coarser scale. Thus, an absolute static pressure sensor **20** combining a number of fluid conducting channels **34**, **44** or **54** and selected gas environments **36**, **46** or **56** with different volume to cross-sectional area ratios can measure absolute static pressure over a variety of pressure ranges at the same point of communication, thereby increasing the effective absolute static pressure range of the sensor.

The invention has been described in detail with particular reference to certain preferred embodiments thereof, but it will be understood that variations and modifications can be effected within the spirit and scope of the invention.

PARTS LIST

10 Printing apparatus
12 Ink reservoir
14 Drive electronics
16 Individually addressable printhead
18 Microfluidic device
20 Absolute static pressure sensor
22 Computer
24 Data
26 Transport Mechanism
28 Receiver
30 Working Fluid
32 First point of communication
34 First fluid conducting channel
36 First selected gas environment
38 First interface
40 First visual scale
42 Second point of communication
44 Second fluid conducting channel
46 Second selected gas environment
48 Second interface
50 Second visual scale
52 Additional point of communication
54 Additional fluid conducting channel
56 Additional selected gas environment
58 Additional interface
60 Additional visual scale

What is claimed is:

1. A method of measuring absolute static pressure at one or more positions along the wall of a microfluidic device transporting a working fluid that is immiscible in a first selected gas environment, comprising the steps of:

(a) providing a first fluid conducting channel having an atmosphere provided by the first selected gas environment under a sealed environment and in communication with the microfluidic device at a first point of communication;

(b) providing a first visual scale adjacent to the first fluid conducting channel; and

(c) transporting the working fluid under pressure conducted by the microfluidic device into the first fluid conducting channel such that the volume transported into such first fluid conducting channel varies depending upon the absolute static pressure of the working fluid at the first point of communication, whereby the absolute static pressure at the first point of communication is visually determined depending on the position of the interface of the working fluid and the first selected gas environment in the first fluid conducting channel when compared with the first visual scale.

2. The method of claim **1** further including providing a second fluid conducting channel and a second visual scale adjacent to the second fluid conducting channel and in communication with the microfluidic device at a second point of communication whereby the static pressure differential in the microfluidic device between the first and second points of communication can be visually determined.

3. The method of claim **1** further including at least one additional fluid conducting channel in direct communication with the first fluid conducting channel at an additional point of communication and providing an atmosphere by an additional selected gas in a sealed environment for such additional fluid conducting channel and an additional visual scale adjacent to the additional fluid conducting channel and wherein the additional selected gas environment associated with the additional fluid conducting channel has a different volume to cross-sectional area ratio than the first selected gas environment in the first fluid conducting channel.

4. The method according to claim **1** wherein the microfluidic device is a channel, reservoir, chamber, conduit, pump, valve, mixer, needle or a system incorporating any combination of these.

5. The method according to claim **1** wherein the first selected gas is air, nitrogen, argon, neon, helium, oxygen, hydrogen, water vapor, carbon monoxide, carbon dioxide, or a miscible combination of these.

6. The method according to claim **1** wherein the working fluid is water, ink, ethylene glycol, methanol, ethanol, isopropanol, oil, acetone, an organic solvent, a biological fluid, a solution of a chemical analyte, or a miscible combination of these.

7. A method of measuring flow rate between two or more positions along a microfluidic channel transporting a working fluid that is immiscible in a first selected gas environment, comprising the steps of:

(a) providing a first fluid conducting channel having an atmosphere provided by the first selected gas environment under a sealed environment and in communication with the microfluidic channel at a first point of communication;

(b) providing a first visual scale adjacent to the first fluid conducting channel; and

(c) transporting the working fluid under pressure conducted by the microfluidic channel into the first fluid conducting channel such that the volume transported into such first fluid conducting channel varies depending upon the absolute static pressure of the working fluid in the microfluidic channel at the first point of communication, whereby the absolute static pressure at the first point of communication is visually determined depending on the position of the interface of the working fluid and the first selected gas environment in the first fluid conducting channel when compared with the first visual scale;

(d) providing a second fluid conducting channel having an atmosphere provided by the second selected gas under a sealed environment and in communication with the microfluidic channel at a second point of communication;

(e) providing a second visual scale adjacent to the second fluid conducting channel;

(f) transporting the working fluid under pressure conducted by the microfluidic channel into the second fluid conducting channel such that the volume transported into such second fluid conducting channel varies depending upon the absolute static pressure of the working fluid in the microfluidic channel at the second point of communication, whereby the absolute static pressure at the second point of communication can be visually determined depending on the position of the interface of the working fluid and the second selected gas environment in the second fluid conducting channel when compared with the second visual scale;

(g) providing an additional fluid conducting channel having an atmosphere provided by an additional selected gas under a sealed environment and in communication with the microfluidic channel at an additional point of communication;

(h) providing an additional visual scale adjacent to the additional fluid conducting channel;

(i) transporting the working fluid under pressure conducted by the microfluidic channel into the additional fluid conducting channel such that the volume transported into such additional fluid conducting channel varies depending upon the absolute static pressure of the working fluid in the microfluidic channel at the additional point of communication, whereby the absolute static pressure at the additional point of communication can be visually determined depending on the position of the interface of the working fluid and the additional selected gas environment in the additional fluid conducting channel when compared with the additional visual scale;

(j) calculating the average static pressure gradient between any two of the points of communication by dividing the difference in absolute static pressure measured at the two points of communication by the separation distance between the two points of communication; and

(k) calculating the flow rate of the working fluid through the microfluidic channel between any two of the points of communication from the average static pressure gradient between any two of the points of communication and the physical properties of the working fluid using predetermined formulae for laminar flow in microchannels with various cross-sections.

8. The method of claim **7** further including at least one additional fluid conducting channel in direct communication with the first fluid conducting channel at an additional point of communication and providing an atmosphere by an additional selected gas environment in a sealed environment for such additional fluid conducting channel and an additional visual scale adjacent to the additional fluid conducting channel and wherein the additional selected gas environment associated with the additional fluid conducting channel has a different volume to cross-sectional area ratio than the first selected gas environment in the first fluid conducting channel.

9. The method according to claim **7** wherein the first selected gas is air, nitrogen, argon, neon, helium, oxygen, hydrogen, water vapor, carbon monoxide, carbon dioxide, or a miscible combination of these.

10. The method according to claim **7** wherein the working fluid is water, ink, ethylene glycol, methanol, ethanol, isopropanol, oil, acetone, an organic solvent, a biological fluid, a solution of a chemical analyte, or a miscible combination of these.

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